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LLNL-TR-648792

Final report on NA22 Project: A Comprehensive Capability to Use Prompt Fission Signatures to Detect SNM

R. Vogt

January 27, 2014

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Final report on NA22 Project:

A Comprehensive Capability to Use Prompt Fission Signatures to Detect SNM

webPMIS Project Number: LL11-Prompt-Fission-Sig-PD03

B&R Code: NN2001-03

PRINCIPAL INVESTIGATOR:	Ramona L. Vogt, 925-423-8210
LLNL PROJECT MANAGER:	Adam Bernstein, 925-422-8761 (Years 1 & 2)
	Steve Payne, 925-423-0570 (Year 3)
LLNL POINT OF CONTACT:	Jenni Pruneda, 925-422-3037
HQ PROGRAM MANAGER:	David Beach, 202-586-0346
HQ OFFICE MANAGER:	Edward Watkins, 202-586-4200

Project Description

The objective of this project is to provide a general capability that will facilitate detection of high-sensitivity nuclear material for both active interrogation and passive systems. Currently these systems are able to use only a small fraction of the information carried by particles emitted during fission. Our improvements in physics modeling and simulation tools would enable exhaustive use of prompt fission signatures. In particular, this project will provide a computationally efficient event-by-event description of fission that explicitly describes all of the correlations associated with the production and subsequent decay of fragments formed in fission. We will use existing data to validate our model as far as possible, including trying to make use of data from current NA22 funded projects. Once complete, we will make our code, `FREYA`, publicly available either as a standalone code or as a module in Monte Carlo transport codes.

I. INTRODUCTION

The objective of this project was to develop a comprehensive fission signature capability that could be leveraged to dramatically increase the performance of SNM detection systems. This capability, embodied in the event-by-event Monte Carlo simulation `FREYA`, is based on improvements in the physics describing the complicated process of nuclear fission and the concurrent development of simulation tools to account for signatures of fission observed by detectors. Part of our model development includes validating the model against existing data as far as possible. Our work focuses on the prompt signatures of fission: neutron and photon emission.

`FREYA` goes beyond the previously-employed average fission models which do not conserve energy or momentum but instead sample neutrons from a common average neutron spectrum regardless of the neutron multiplicity and thus cannot address correlations between observables. In the course of this lifecycle plan we were able to address correlations between energy and number of neutrons; energy and number of photons; kinematic correlations between neutrons; correlations between neutron and photon emission.

In the following, the basic physics encapsulated in `FREYA` is described and some characteristic results are presented. Simulations showing that the correlations addressed by the project can survive in a real detector are also presented. The appendix contains some description of the personnel involved in the project; a list of publications and presentations resulting from the project; and a list of the deliverables for each fiscal year of the project. The journal articles and proceedings associated with each deliverable, where applicable) are indicated.

II. PHYSICS OF `FREYA`

We had originally begun to develop `FREYA` for data evaluation. The event-by-event feature seemed the most obvious direction for development because only in this way could kinematic information on all particles involved be retained, allowing arbitrary correlation studies. Our code `FREYA` (Fission Reaction Event Yield Algorithm) [1–6]. simulates complete fission events with full kinematic information on the fission products and the emitted neutrons and photons. `FREYA` uses measured observables to improve our treatment of the fission process. Thus it is a potentially powerful tool for bridging the gap between current microscopic models and important fission observables as well as for improving estimates of fission characteristics for applications. Below we briefly describe the physics of the complete model, developed over the course of the project lifecycle.

We start with a fissile nucleus ${}^{A_0}Z_0$ with excitation energy E_0^* that undergoes binary fission into a heavy ${}^{A_H}Z_H$ and a light fragment ${}^{A_L}Z_L$. The fragment masses are obtained from experimental mass yields $Y(A)$, see Ref. [2]. The fragment charge, Z_f, is selected from the Gaussian form, $P_{A_f}(Z_f) \propto \mathrm{e}^{-(Z_f-\bar{Z}_f(A_f))^2/2\sigma_Z^2}$. The fragments are assumed to have, on average, the same charge-to-mass ratio as the fissioning nucleus, $\bar{Z}_f(A_f) = A_f Z_0/A_0$. The charge of the complementary fragment then follows using $Z_L + Z_H = Z_0$ [2].

Once the mass and charge of the two fragments have been selected, the Q value of the fission channel is the difference between the total mass of A_0 and the fragment ground-state masses, $Q_{LH} = M(A_0) - M_L - M_H$. The Q_{LH} value is divided between the total kinetic energy (TKE) and the total excitation energy (TXE) of the fragments. The average TKE is assumed to take the form $\overline{\mathrm{TKE}}(A_H, E_\mathrm{n}) = \overline{\mathrm{TKE}}_\mathrm{data}(A_H) + d\mathrm{TKE}(E_\mathrm{n})$ where E_n is the incident neutron energy. The first term is extracted from data while the second is adjusted to the measured average neutron multiplicity, $\overline{\nu}(E_n)$.

We assume that the system is in a rigidly rotating dinuclear configuration just prior to scission with total angular momentum $\boldsymbol{S}_0$. It is rather small for thermal-neutron induced fission and vanishes entirely for spontaneous fission. We treat the fragments as spheres, for simplicity, and we denote their moments of inertia by $\mathcal{I}_i$, for $i = L, H$. The moment of interia of the relative fragment motion is given by $\mathcal{I}_R = \mu R^2$, where $\boldsymbol{R} = \boldsymbol{R}_L - \boldsymbol{R}_H$ is the position of the light fragment relative to the heavy one and μ is the reduced mass of the fragments. At scission each fragment will inherit some of $\boldsymbol{S}_0$, $\boldsymbol{S}_i = (\mathcal{I}_i/\mathcal{I})\boldsymbol{S}_0$, where $\mathcal{I} = \mathcal{I}_L + \mathcal{I}_H + \mathcal{I}_R$ is the total moment of inertia. The remainder of $\boldsymbol{S}_0$ will become the angular momentum of the relative fragment motion. In addition to the average fragment spins arising from the overall dinuclear rotation, the two fragments also acquire spin fluctuations, $\delta\boldsymbol{S}_L$ and $\delta\boldsymbol{S}_H$. Generally, a dinuclear system has six normal modes of rotation [7], namely *tilting* and *twisting*, in which the fragments rotate in the same or in the opposite sense around the dinuclear axis $\boldsymbol{z} = R/\boldsymbol{R}$, and *wriggling* and *bending*, in which the fragments rotate in the same or in the opposite sense around an axis perpendicular to the dinuclear axis. (The two latter types of modes are then each doubly degenerate.) We consider only the latter four modes because the agitation of the former two tends to be suppressed due to the constricted neck [7].

The contribution to the rotational energy from these four dinuclear rotational modes is given by

$$\delta E_\mathrm{rot} = \boldsymbol{s}_+^2/2\mathcal{I}_+ + \boldsymbol{s}_-^2/2\mathcal{I}_- \ , \tag{1}$$

where the normal modes have the form $\boldsymbol{s}_\pm = (s_\pm^x, s_\pm^y, 0)$, with the plus referring to the wriggling modes (in which the rotations of the two fragments are parallel) and the minus to the bending modes (in which the rotations of the two fragments are opposite). The associated moments of inertia are

$$\mathcal{I}_+ = (\mathcal{I}_L + \mathcal{I}_H)\mathcal{I}/\mathcal{I}_R \ , \quad \mathcal{I}_- = \mathcal{I}_L\mathcal{I}_H/(\mathcal{I}_L + \mathcal{I}_H) \ . \tag{2}$$

The statistical fragment excitation energy is reduced correspondingly. It is assumed that these normal dinuclear rotational modes are being agitated statistically during the scission process. Thus, in each event, the values of $\boldsymbol{s}_\pm$ are being sampled from distributions of the form

$$P_\pm(\boldsymbol{s}_\pm = (s_\pm^x, s_\pm^y, 0))\, ds_\pm^x ds_\pm^y \sim \mathrm{e}^{-s_\pm^2/2\mathcal{I}_\pm T_S} ds_\pm^x ds_\pm^y, \tag{3}$$

where the "spin temperature" T_S is, for now, regarded as a global but somewhat adjustable parameter. The corresponding fluctuating angular momentum components of the individual fragments in our approach are then

$$\delta S_L^k = (\mathcal{I}_L/\mathcal{I}_+)s_+^k + s_-^k \ , \quad \delta S_H^k = (\mathcal{I}_H/\mathcal{I}_+)s_+^k - s_-^k \ , \tag{4}$$

for $k = x, y$, whereas $\delta S_i^z = 0$. Consequently, the total angular momenta of the fragments are $\boldsymbol{S}_i' = \boldsymbol{S}_i + \delta\boldsymbol{S}_i$. The orbital angular momentum is adjusted correspondingly.

After the average total fragment kinetic energy, $\overline{\mathrm{TKE}}$, has been sampled, the combined average statistical fragment excitation energy, $\overline{\mathrm{TXE}}$, follows from energy conservation, $\overline{\mathrm{TXE}} = \overline{E}_L^* + \overline{E}_H^* \doteq Q - \overline{\mathrm{TKE}} - E_\mathrm{rot}$.

If the fragments are in mutual thermal equilibrium, their temperatures are equal, $T_L = T_H$, and their average statistical excitation energy is proportional to the level-density parameter, *i.e.* $\overline{E}_f^* \sim a_f$. `FREYA` first assigns average excitations, $\acute{E}_f^*$, based on such an equipartition, $\acute{E}_f^* = a_f(\tilde{E}_f^*)\overline{\mathrm{TXE}}/(a_L(\tilde{E}_L^*) + a_H(\tilde{E}_H^*))$ where $\tilde{E}_f^* = (A_f/A_0)\overline{\mathrm{TXE}}$. Subsequently, because the observed neutron multiplicities suggest that the light fragments are more excited (probably due to their greater distortion at scission), the average excitations are adjusted as $\overline{E}_L^* = x\acute{E}_L^*$, $\overline{E}_H^* = \overline{\mathrm{TKE}} - \overline{E}_L^*$, where $x > 1$ is a parameter.

After the mean excitation energies have been assigned, `FREYA` accounts for thermal fluctuations. The fragment temperature T_f is obtained from $\overline{U}_f \equiv U_f(\overline{E}_f^*) = a_f T_f^2$, where $U(E^*) = E^*$. The variance in the excitation E_f^* is then $\sigma_f^2 = 2\overline{U}_f^* T_f$. Therefore, for each of the two fragments, a thermal fluctuation δE_f^* is sampled from a normal distribution of variance σ_f^2 and the fragment excitation energies are modified accordingly, $E_f^* = \overline{E}_f^* + \delta E_f^*$. Energy conservation causes a compensating fluctuation in TKE leading to $\mathrm{TKE} = \overline{\mathrm{TKE}} - \delta E_L^* - \delta E_H^*$ [4].

Neutron evaporation occurs after the fragments have reached their asymptotic velocities. For a fragment of statistical excitation E^*, the maximum temperature in its evaporation daughter, $T_{\rm max}$, is obtained from $aT_{\rm max}^2 = E^* - S_n(Z,A)$, where $S_n(Z,A)$ is the neutron separation energy. The neutron kinetic energy ϵ is sampled from $f_n(\epsilon) \sim \epsilon \exp(-\epsilon/T_{\rm max})$. Neutron evaporation from FREYA accounts for angular momentum in two regards: the emitting nucleus may generally be rotating and the emitted neutron carries away some angular momentum. The emission point is selected randomly on the nuclear surface and a neutron is then emitted from the local surface element and subsequently boosted by the local rotational velocity of the emission point. The linear and angular momentum recoils are taken into account. Neutrons are emitted as long as the Q value for emission exceeds $E_{n,\rm cut}$ where photon emission takes over.

After neutron evaporation has ceased, the residual product nucleus has a statistical excitation energy of $E^* < S_n(Z,A) + E_{n,\rm cut}$ and de-excites by sequential photon emission. First the statistical excitation energy is radiated away by sequential photon emission, leaving a cold but rotating product nucleus which then emits photons along the yrast line.

Statistical photon emission is treated analogous to neutron evaporation except there is no separation energy for photons. Since the photons are massless, we introduce an infrared cut-off energy. Furthermore, there is an extra energy factor in the photon phase space, $f_\gamma(E) \sim E^2 \exp(-E/T)$ where T, the maximum possible temperature after emission, is equal to the nuclear temperature prior to emission. Photons are emitted isotropically in the frame of the emitter nucleus. Emission continues until the available statistical excitation energy has been exhausted. The angular momentum is then disposed of by simulating a stretched E2 cascade. Each photon emission reduces the angular momentum by two units and the energy by $E = (1/2)[S^2 - (S-2)^2]\hbar^2/\mathcal{I} = 2(S-1)\hbar^2/\mathcal{I}$. At the end of the cascade, when $S < 2$, a single final photon is emitted with the remaining excitation energy.

III. ILLUSTRATIVE RESULTS

A. Physics results

In the first year of the project, we expanded the utility of FREYA to compare and contrast correlations between neutron observables in spontaneous and thermal fission of ^{240}Pu, ^{240}Pu(sf) and ^{239}Pu(n$_{\rm th}$,f) respectively, as well as between ^{238}U(sf) and ^{235}U(n$_{\rm th}$,f). We also studied these observables in the spontaneous fission of ^{252}Cf, often used as a calibrator for other fission measurements, and ^{244}Cm. While the focus was narrower in the last two journal articles of the project, primarily ^{252}Cf, ^{235}U(n$_{\rm th}$,f) and ^{239}Pu(n$_{\rm th}$,f), FREYA can handle all of the cases mentioned above, including neutron-induced fission of ^{235}U and ^{239}Pu up to incident neutron energies of 20 MeV. The multiplicity-gated spectral shapes obtained for the various cases considered are shown on the right-hand side of Fig. 1. Results are presented for multiplicities up to $\nu = 6$. It is apparent that the spectra become progressively softer at higher multiplicities, as one would expect because more neutrons are sharing the available energy. This type of elementary conservation-based correlation feature is not provided by the standard models of fission. The tails of the prompt fission neutron spectra from ^{240}Pu(sf) are longer and broader than those from ^{239}Pu(n$_{\rm th}$,f) even though the average energies are smaller and fewer neutrons are emitted. The most energetic neutrons at high multiplicity are emitted from ^{252}Cf(sf) where the spectra are also rather closely clustered around the mean.

The event-by-event nature of FREYA makes it straightforward to extract the angular correlation between two evaporated neutrons which cannot be addressed with the standard models of fission. The left-hand side of Fig. 1 shows this quantity for the neutrons resulting from fission induced by thermal neutrons on ^{239}Pu as well as neutron correlations in spontaneous fission. The results are shown for neutrons with kinetic energies above thresholds at $E = 0.5$, 1 and 1.5 MeV. The angular modulation grows somewhat more pronounced as the threshold is raised albeit with correspondingly reduced statistics.

The neutrons tend to be either forward or backward correlated. The backward correlation appears to be somewhat favored. We have previously analyzed the case of ^{239}Pu(n$_{\rm th}$,f) for $\nu = 2$, breaking it down to three separate contributions: both neutrons from the light fragment, both from the heavy fragment, and one neutron emitted from each fragment [8]. There is a significant correlation at $\theta_{12} = 0$ when both neutrons are emitted from the same fragment, with a higher peak for the case when both neutrons are emitted from the light fragment due to its higher velocity. On the other hand, when one neutron is emitted from each fragment, their direction tends to be anti-correlated due to the relative motion of the emitting fragments, resulting in a peak at $\theta_{12} = 180$. The overall result is a stronger backward correlation because emission from both fragments is most likely. The backward correlation is strongest when the overall neutron multiplicity is low, especially for ^{240}Pu(sf), whereas large multiplicities, as for ^{252}Cf(sf),

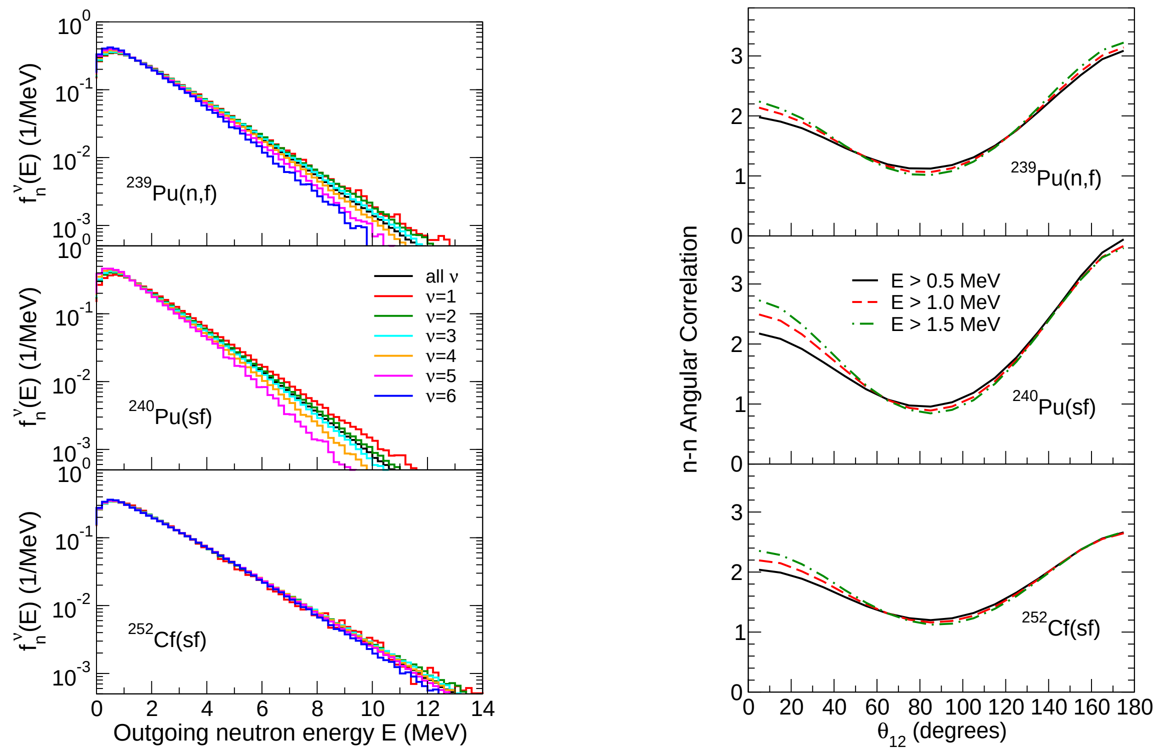

FIG. 1: (Left) The prompt fission neutron spectrum for neutron induced fission of ^{239}Pu (top) and spontaneous fission of ^{240}Pu (middle) and ^{252}Cf (bottom) as a function of outgoing neutron energy. The FREYA results are shown averaged over all neutron multiplicities as well as the results for neutron multiplicities up to $\nu = 6$. (Right) The angular correlation between two neutrons emitted during neutron induced fission of ^{239}Pu (top) and spontaneous fission of ^{240}Pu (middle) and ^{252}Cf (bottom) as a function of the opening angle between the two neutrons, θ_{12}. The FREYA results are shown for several cuts on neutron kinetic energy: $E > 0.5$ MeV (solid black), 1 MeV (dashed red), and 1.5 MeV (dot-dashed green). These results are from [3].

reduce the angular correlation.

Here FREYA results are compared to the LiBerACE data on neutron-photon correlations are compared to FREYA calculations with $T_S = 0.35$ and 2.75 MeV in Fig. 2. Niefenecker claimed a strong positive neutron-photon correlation [9]. The LiBerACE data [10] instead show only a weak correlation. FREYA produces a slight anticorrelation, as might be expected from simple conservation laws. The lower value of T_S gives both a lower multiplicity and a stronger negative shift between $\nu = 2$ and $\nu = 4$ than the data. For further details, see Ref. [5].

The right-hand side of Fig. 2 shows S. A. Pozzi's result [11] on correlated neutron counts as a function of angle for several neutron energy thresholds compared to FREYA. The results show generally good agreement with the exception of at small angles between detectors where the disagreement can be explained by cross talk: it affects the measurement but not the theory prediction.

B. Applications

For his SORMA poster and proceedings [12], Chris Hagmann adopted the MCNP detector model developed for a large array of liquid scintillators [13] for correlation studies using MCNP5. The detector consists of 64 cells of xylene ($m_{\rm cell} \sim 0.5$ kg), each read out by a single phototube. The cells are symmetrically arranged into octants with an array inner diameter of $\sim$ 60 cm. The detector was designed for fast multiplicity counting and assaying of fissile material. The fast scintillator decay time (few ns) enables faster count rates than He well counters. Neutron-gamma separation is accomplished by pulse-shape discrimination (PSD) with a minimum proton recoil energy of $\sim$ 1 MeV. The detection efficiency for unmoderated fission neutrons with this threshold is 5%.

Neutron-neutron angular correlations were studied in this setup. Almost all of the neutrons in spontaneous and

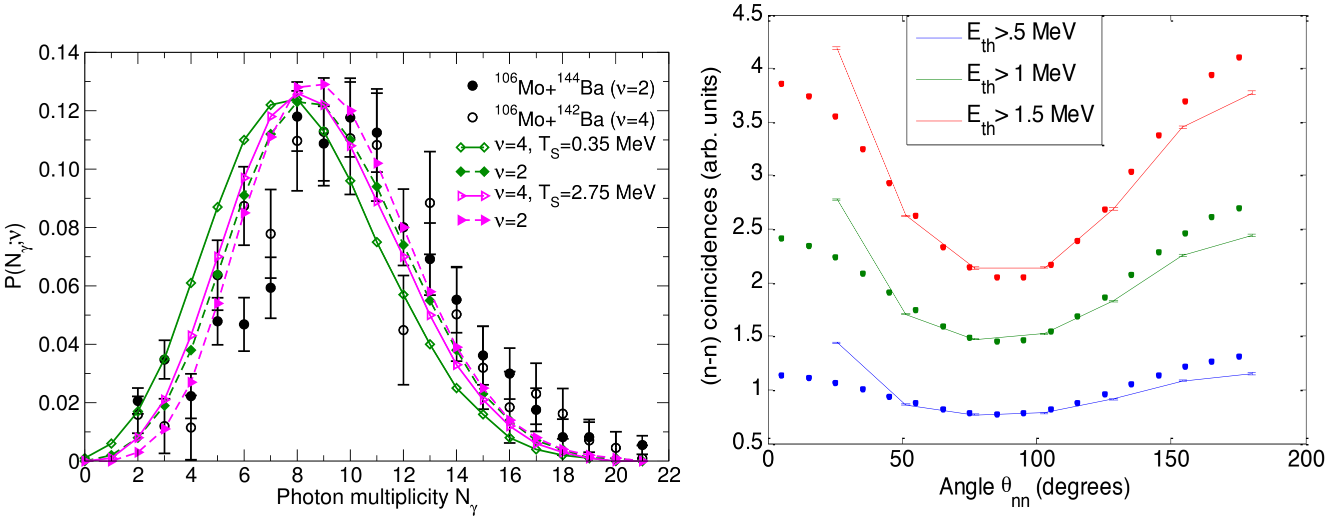

FIG. 2: (Left) Photon emission from ^{252}Cf(sf) [5]. The N_γ distribution gated on ν, averaged over all fragment masses. The solid curves with filled symbols show $\nu = 2$ while the dashed curves with open symbols show $\nu = 4$. The LiBerACE [10] Mo+Ba data with $\nu = 2$ and 4 are also shown. The results are from Ref. [5]. (Right) The `FREYA` results (dotted) compared to measurements [11].

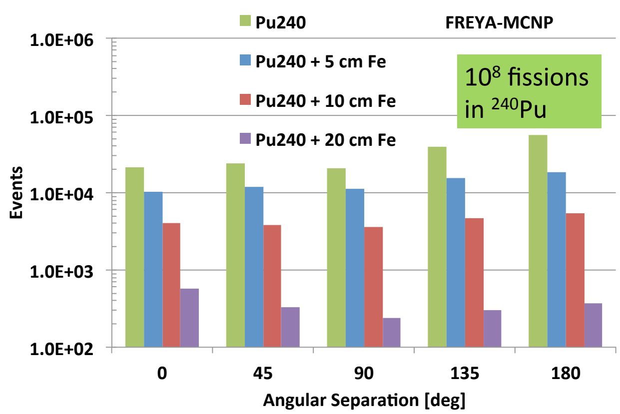

FIG. 3: Angular correlations (using detector octants as the bin size) with a ^{240}Pu(sf) source for different thickness of iron shielding as calculated by `MCNP5` + `FREYA`. The number of fission events is 10^8 [12].

low energy fission are emitted by the fully accelerated fission fragments whose back-to-back motion is imprinted on the neutron directions in the laboratory frame. Thus, small-angle correlations are expected from neutrons emitted from the same fragment, whereas large-angle correlations arise from opposite fragments. `FREYA` evaporates neutrons isotropically in the center-of-mass system of the fragments and boosts them back into the laboratory frame, resulting in angular correlations.

Figure 3 depicts the count distributions of coincidences as a function of angle for a ^{240}Pu(sf) source surrounded by a variable amount of iron shielding. The angular resolution is 45° since all events in an octant were combined in a single bin. For all Fe shielding thicknesses considered, `FREYA` shows distinct angle-dependent correlations, most apparent at 90° and 180°. The number of events decreases with increasing shield thickness due to neutron moderation in the Fe. It is remarkable that the ratio of events at 180° relative to 90° only decreases from 2.7 (0 cm Fe) to 1.6 (20 cm Fe). On the other hand, `MCNP` shows no correlations at large angles. The deviations from isotropy at 0° stem from multiple hits of the same neutron in a single octant and from the requirement that each cell can be triggered only once in a fission chain. Multiple scattering of the same neutron in different cells also contributes counts. This mostly affects the counts at 0° since scattering is more likely into adjacent cells, contributing to the enhancement for large shielding thicknesses. On the other hand, when there is little shielding, the counts at 0° will be suppressed because of the requirement that each cell can trigger only once during a fission chain.

IV. SUMMARY

The project has been carried out successfully. The deliverables were met. In addition to the current code release, the project resulted in 3 journal articles, 7 conference proceedings, an invited book chapter, and 19 presentations and posters at conferences. Further funding was obtained through the NA22 joint project with LANL: Developing Accurate Simulations of Correlated Data in Fission Events.

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy under Contracts No. DE-AC52-07NA27344. The research is also supported by the US Department of Energy National Nuclear Security Administration Office of Nonproliferation and Verification Research and Development.

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Appendix A: Collaborators

There have been 5 people working on the project during its lifetime. The PI and her collaborator at LBNL, Jørgen Randrup, are the developers of `FREYA` and provide the physics input. In FY13, we included about 0.1 FTE for W. E. Ormand at LLNL to provide some information about photon emission from his Hauser-Feshbach code.

Two collaborators have worked on making the inline version of `FREYA` straightforward to use and available to the `MCNP` developers at about 0.3 FTE. For the first half of the project lifecycle, Chris Hagmann worked with us. He made a preliminary interface with `MCNP5` and showed that the correlations that we predicted could survive in a real detector setup. When he was no longer available, Jerome Verbeke took over and made further refinements that would allow `FREYA` to be made available in `MCNP` as an option in the LLNL Fission Library. This was the version, `FREYA1.0`, that was delivered to the `MCNP` development team in June 2013.

Appendix B: Publications and Presentations

The outcome from this project in terms of publications and presentations at meetings, both oral and poster, are given in this appendix. The LLNL report number corresponding to each are given as well except when the principal author or speaker was J. Randrup since he is at LBNL. Unless otherwise indicated, the talks listed were all given by the PI.

- *Journal Articles*:
    1. Event-by-event study of neutron observables in spontaneous and thermal fission, by R. Vogt and J. Randrup, Phys. Rev. C **85** (2011) 044621, LLNL-JRNL-499401.
    2. Event-by-event study of photon observables in spontaneous and thermal fission, R. Vogt and J. Randrup, Phys. Rev. C **87** (2013) 014617, LLNL-JRNL-586192.
    3. Refined treatment of angular momentum in `FREYA`, by J. Randrup and R. Vogt, submitted to Phys. Rev. C, LLNL-JRNL-648553.
- *Conference Proceedings*
    1. Applications of Event-by-Event Fission Modeling with `FREYA`, by R. Vogt and J. Randrup, *Third International Workshop on Compound Nuclear Reactions and Related Topics*, EPJ Web of Conferences **21** (2012) 08007, LLNL-CONF-500097.
    2. `FREYA`-A new Monte Carlo code for improved modeling of fission chains, by C. A. Hagmann, J. Randrup and R. Vogt, *2012 IEEE Symposium on Radiation Measurements and Applications*, IEEE Transactions on Nuclear Science **60** (2013) 545, LLNL-CONF-561431.
    3. Event-by-Event Fission Modeling of Prompt Neutrons and Photons from Neutron-Induced and Spontaneous Fission with `FREYA`, R. Vogt and J. Randrup, in the proceedings of the 5$^{\rm th}$ *International Conference on Fission and Properties of Neutron-rich Nuclei*, edited by J. H. Hamilton and A. V. Ramayya, World Scientific (2013), p. 589, LLNL-CONF-609746.
    4. Brownian Shape Dynamics in Nuclear Fission, J. Randrup and P. Moller, in the proceedings of the 5$^{\rm th}$ *International Conference on Fission and Properties of Neutron-rich Nuclei*, edited by J. H. Hamilton and A. V. Ramayya, World Scientific (2013), p. 613.
    5. Event-by-Event Fission Modeling of Prompt Neutrons and Photons from Neutron-Induced and Spontaneous Fission with `FREYA`, R. Vogt and J. Randrup, Phys. Procedia **47** (2013) 82, LLNL-CONF-623913.
    6. Brownian Shape Dynamics in Fission, J. Randrup and P. Moller, Phys. Procedia **47** (2013) 3.
    7. Event-by-Event Fission Modeling of Prompt Neutrons and Photons from Neutron-Induced and Spontaneous Fission with `FREYA`, R. Vogt and J. Randrup, to be published in the proceedings of *Twelfth International Conference on Nuclear Data for Science and Technology (ND2013)*, LLNL-CONF-623813.
- *Books*:
    1. 100 Years of Subatomic Physics, edited by E. M. Henley and S. D. Ellis, World Scientific (2013). J. Randrup and I contributed invited review Chapter 5: Nuclear Fission, LLNL-JRNL-591732.

- *Code*:

    1. `FREYA1.0`, LLNL-CODE-636753.

- *External Presentations and Posters*:

    1. *RadSensing 2011*, Sandia National Laboratory, Livermore, CA, USA, 6/11. Poster: "A Comprehensive Capability to Use Prompt Signatures of Fission to Detect SNM", presented by C. Hagmann, LLNL-POST-485525.
    2. *Compound Nuclear Reactions 2011 (CNR*11)*, Prague, Czech Republic, 9/11. Talk:"Applications of Event-by-Event Fission Modeling with `FREYA`", LLNL-PRES-500133.
    3. *CSWEG/USNDP '11*, BNL, Upton, NY, USA, 11/11. Talk: "Applications of Event-by-Event Fission Modeling with `FREYA`", LLNL-PRES-513462.
    4. IAEA Coordinated Research Project meeting on the *Prompt Fission Neutron Spectrum of Actinides*, IAEA Headquarters, Vienna, Austria, 12/11. Invited talk:"Modeling the prompt fission neutron spectrum with `FREYA`", LLNL-PRES-520241.
    5. APS April Meeting, Atlanta, GA, USA, 3-4/12. Talk: "Event-by-event fission modeling with `FREYA`", LLNL-PRES-428095.
    6. *SORMA West 2012*, 2012 IEEE Symposium on Radiation Measurements and Applications, Oakland, CA, USA, 5/12, presented by C. A. Hagmann, Poster: "`FREYA`-A new Monte Carlo code for improved modeling of fission chains", LLNL-POST-556937.
    7. *RadSensing 2012*, Sandia Laboratory, Albuquerque, NM, USA, 6/12. Invited talk: "A Comprehensive Capability to Use Prompt Fission Signatures to Detect SNM", LLNL-PRES-558093.
    8. *Heating Nuclei, Boiling Black Holes ... and Burning Rubber*, McGill University, Montreal, Canada, 6/12. Invited talk: "`FREYA`: A Heavy-Ion Physicist's Approach to Fission", LLNL-PRES-557921.
    9. *Heating Nuclei, Boiling Black Holes ... and Burning Rubber*, McGill University, Montreal, Canada, 6/12. Invited talk: "1st order phase transition; or fragment mass distribution in fission", presented by J. Randrup.
    10. MCNP Workshop, LANL, Los Alamos, NM, USA, 10/12. Invited talk: "Event-by-Event Fission Modeling of Prompt Neutrons and Photons from Neutron-Induced and Spontaneous Fission with `FREYA`", LLNL-PRES-592252.
    11. MCNP Workshop, LANL, Los Alamos, NM, USA, 10/12. Invited talk: "LLNL Fission Library and `FREYA`", presented by J. Verbeke, LLNL-PRES-593995.
    12. 5$^{\text{th}}$ International Conference on Fission and Properties of Neutron-Rich Nuclei, Sanibel Island, FL, USA, 11/12. Invited talk: "Event-by-Event Fission Modeling of Prompt Neutrons and Photons from Neutron-Induced and Spontaneous Fission with `FREYA`", LLNL-PRES-592252.
    13. 5$^{\text{th}}$ International Conference on Fission and Properties of Neutron-Rich Nuclei, Sanibel Island, FL, USA, 11/12. Invited talk: "Brownian Shape Dynamics in Fission", presented by J. Randrup.
    14. Theory 2 Workshop on Nuclear Fission Dynamics and the Emission of Prompt Neutrons and Gamma Rays, Biarritz, France, 11/12. Invited talk: "Event-by-Event Fission Modeling of Prompt Neutrons and Photons from Neutron-Induced and Spontaneous Fission with `FREYA`", LLNL-PRES-592252.
    15. Theory 2 Workshop on Nuclear Fission Dynamics and the Emission of Prompt Neutrons and Gamma Rays, Biarritz, France, 11/12. Invited talk: "Brownian Shape Dynamics in Fission", presented by J. Randrup.
    16. Nuclear Data 2013, New York, NY, USA, 3/13. Talk: "Event-by-Event Fission Modeling of Prompt Neutrons and Photons from Neutron-Induced and Spontaneous Fission with `FREYA`". LLNL-PRES-623592.
    17. *Weapons & Materials Security Team Program Review Meeting (WMS 2013)*, Sandia National Laboratory, Livermore, CA, USA, 4/13. Poster: "A Comprehensive Capability to Use Prompt Signatures of Fission to Detect SNM", LLNL-POST-626982.
    18. APS April Meeting, Denver, CO, USA, 4/13. Talk: "Event-by-Event Fission Modeling of Prompt Neutrons and Photons from Neutron-Induced and Spontaneous Fission with `FREYA`", LLNL-PRES-632872.
    19. *CSWEG/USNDP '13*, BNL, Upton, NY, USA, 11/13. Talk: "`FREYA` Update", LLNL-PRES-646392.

Appendix C: Project Deliverables

FY11

- Journal article describing ^{252}Cf spontaneous fission and its relevant correlations in `FREYA` submitted for publication (Journal article 1)

FY12

- Journal article describing photon energy-number correlations and photon-neutron correlations in `FREYA` submitted for publication (Journal article 2)
- Article describing functionality of inline `FREYA` neutron module submitted for publication in technical journal (Conference proceeding 2)

FY13

- Journal article on angular momentum effects in fission and how they affect correlations submitted for publication (Journal article 3)
- Make inline `FREYA` module, including gamma emission and angular momentum effects available to user community (`FREYA1.0` released as LLNL-CODE-636753, delivered to MCNP group at LANL on 20 June 2013. This version includes most complete neutron module, they want to stage things more so additional refinements will be in the version produced in the next lifecycle plan.)